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Factors Affecting the Perception of Luning in Monocular Regions of Partial Binocular Overlap Displays

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Luning is a detrimental visual effect characterized by a subjective darkening of the visual field in the monocular regions of partial binocular overlap displays. The effect of a number of factors on the magnitude of luning was investigated. These factors include: (1) the convergent versus the divergent display modes for presenting a partial binocular overlapping field-of-view, (2) the display luminance level, (3) the placement of either black or white contours versus no (null) contours on the binocular overlap border, and (4) the increasing or decreasing of the luminance of the monocular side regions relative to the binocular overlap region. Eighteen Army student aviators served as subjects in a repeated measures design. The percentage of time luning was seen was the measure of the degree of luning. The results indicated that the divergent display mode systematically induced more luning than the convergent display mode under the null contour condition. Adding black contours reduced luning in both the convergent and divergent display modes, where the convergent mode retained its relatively lower magnitude of luning. The display luminance level had no effect on luning for the null or black contour conditions. Adding white contour reduced luning by an amount which depended on display
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luminance where there was less luning for lower display luminance levels, but no systematic effect of display mode. Changing the luminance of the monocular regions (relative to the binocular overlap region) reduced the amount of luning, where a decrease in luminance produced more of a reduction in luning than an increase. When a partial binocular overlap display is needed to present a larger field-of-view to aviators in helmet-mounted displays, the convergent display mode with black contours on the binocular overlap borders appears to be the most reliable of the conditions tested to systematically reduce luning. Additional factors are also discussed.

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Introduction

Small fields-of-view (FOV) are detrimental to the visual tasks required of military pilots (Osgood and Wells, 1991; Wells, Venturino and Osgood, 1989). In order to increase the extent of the visual world available to U.S. Army helicopter pilots using helmet mounted displays (HMD), without incurring increases in size, or weight, or losses in central resolution, an unusual method of display--partial binocular overlap--has been proposed. However, increasing the FOV by this method has been the cause of some concern (Alam et al., 1992; Edgar et al., 1991; Kruk and Longridge, 1984; Landau, 1990; Moffitt, 1989). One detrimental consequence of a partial binocular overlap display mode is a perceptual effect known as luning, which is a subjective darkening in the FOV (Moffitt, 1989). The purpose of our study was to quantify this phenomenon under different display conditions. First, we define a few concepts to avoid the ambiguity of the literatures on vision and display systems (Farrell and Booth, 1984).

Background concepts

In the visual displays described here, **background** is the black region surrounding the **visual fields** which are the intentionally stimulated visual areas seen by each eye. Access to the visual world is assumed to occur only through these artificial visual fields. **Field-of-view** (FOV) refers to the total extent of the visual world that is seen in an HMD when both eyes are open. It includes what is seen by both eyes together as well as what is seen by each eye alone. The portion of the visual world that one eye sees is referred to as its **monocular field**. The portion of the visual world that both eyes see together is referred to as the **binocular overlap region**, and the portion of the FOV that only one eye sees is a **monocular region**. Thus the FOV may consist of a binocular overlap region and a monocular region for each eye.

In our design, and in normal human vision, a monocular field consists of two areas, a monocular region seen exclusively by one eye and the binocular overlap region which can be seen by both eyes. Separating these two areas of the monocular field is the **binocular overlap border**. The term **dichoptic** refers to the situation where there is simultaneous but dissimilar stimulation to the two eyes; thus a monocular region and its corresponding region in the other eye, as well as the binocular border, are dichoptic. The binocular attainment of **singleness of vision** results from the **binocular fusion** of monocular stimuli in corresponding retinal regions of each eye. **Diplopia**, or double vision, results when corresponding monocular stimuli fail to be fused.

When the two eyes are presented with exactly the same portion of the visual world, the viewing situation is referred to as the **full binocular overlap display mode**. In this case the FOV consists solely of a binocular overlap region, in which the two monocular fields are coincident and there are no monocular regions. The **partial binocular overlap display mode** occurs when each of the two eyes sees a portion of the visual world in common--the binocular overlap region--and, in addition, each eye sees an exclusive portion of the visual world in the monocular region (see Grigsby and Tsou, 1993; Moffitt, 1991; and Moffitt and Melzer, 1991).

Partial binocular overlap displays contain binocular overlap borders, which in terms of the FOV separate the binocular overlap region and the monocular regions. In terms of the monocular fields, these borders separate the portion exclusively seen by one eye from the portion seen in common with the other eye. In normal unencumbered vision, the binocular overlap borders, dividing the natural FOV, are not experienced (see Gibson, 1979, for a good discussion), and are only cognitively identified and located with attentional effort. However, in artificial viewing situations such as HMDs, where the monocular fields are smaller than in natural viewing, these borders are accompanied by a perceptual effect that in the display literature has come to be known as luning (CAE Electronics, 1984; Moffitt, 1989).

Luning and related phenomena

Luning is a visual perception characterized by a subjective darkening of the visual field in the monocular regions of partial binocular overlap displays. It was so named (Moffitt, 1989) because of the crescent shapes of the darkened monocular regions adjacent to the circular binocular overlap region. It is most pronounced near the binocular overlap border separating the monocular and binocular regions, gradually fading with increasing distance from the border. The prominence of luning fluctuates over time and appears not to be strongly under attentional control (see Figure 1).

Luning may be related to binocular rivalry and suppression. **Binocular rivalry** refers to the alterations in the appearance of a binocular stimulus which is dichoptic, i.e., where each eye's image alternately dominates the phenomenal binocular FOV by suppressing the other eye's input. Over time, one and then the other eye may successfully compete and dominate awareness. **Suppression** refers to the phenomenal disappearance of one eye's input due to **monocular dominance** by the other eye. Partial suppression refers to the partial disappearance of one eye's input. In the partial binocular overlap display mode, each eye's monocular region is the result of dichoptic competition between a portion of its monocular field and the other eye's monocular field border and dark background. If the background is completely suppressed, the total FOV looks natural, where the binocular and monocular regions are both seen as one continuous visual world. If an eye's monocular region is partially suppressed by the dark background of the other eye, then this dark background will appear in monocular regions of the first eye with the greatest darkening---luning---occurring near the binocular overlap border.

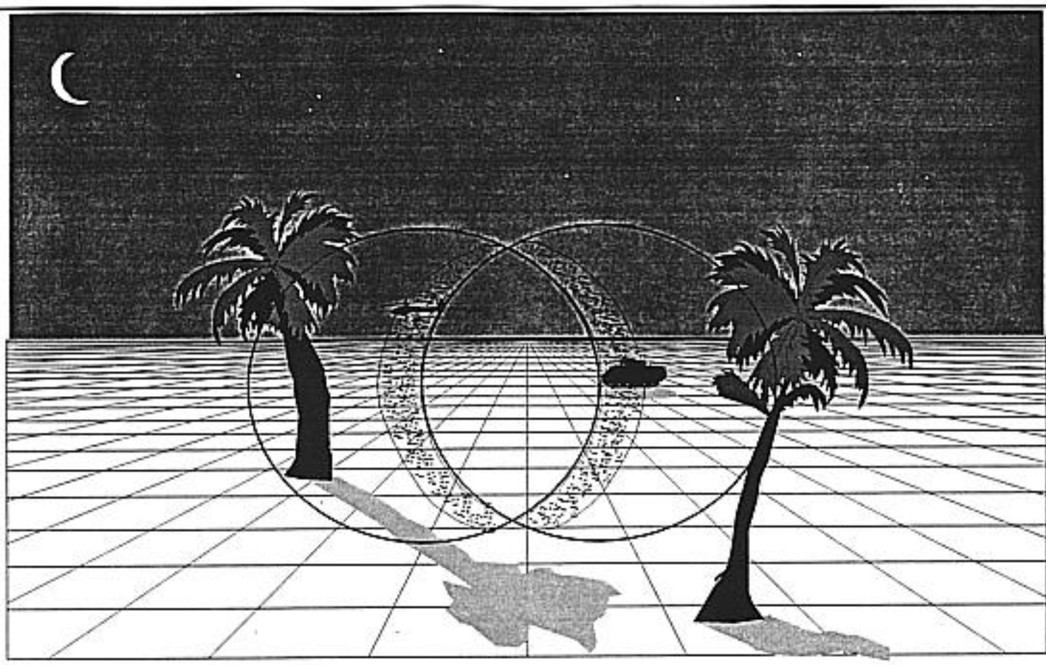

Figure 1. A helicopter pilot's view of the visual world using an HMD in a partial binocular overlap display mode. The helicopter in the left visual field and the armored personnel carrier in the right visual field are each in monocular regions near the binocular overlap border, where luning occurs, as indicated by the shading. If the right eye is viewing the circular field containing the armored personnel carrier, the display mode is divergent. If instead, the left eye is viewing this region, the display mode is convergent. Luning has been reported to be more severe in the divergent display mode.

In the monocular regions of partial binocular overlap displays, both the dichoptic differences in luminance and the presence of the monocular edge--the luminance drop--at the binocular overlap border likely affect luning. This luminance transition between the monocular field and the background occurs in what we shall refer to as the **noninformational eye**. During fusion it is matched to a region within the monocular field of the **informational eye**. There are a number of interocular inhibitory processes in addition to binocular rivalry of dichoptic stimuli (Fox, 1991), which may also contribute to luning (e.g., see Gur, 1991, on Ganzfeld fade-out and blackout, and Bolanowski and Doty, 1987, on blankout). Binocular rivalry and the interocular inhibitory process of suppression due to rivalry between dichoptic stimuli is our working hypothesis of luning. There are different types of binocular rivalry including piecemeal dominance, binocular superimposition, and binocular transparency (Yang, Rose and Blake, 1992). Binocular transparency describes the percept when both dichoptic stimuli are seen simultaneously, but appear "scissioned," or segregated in depth; superimposition describes the situation in which both dichoptic stimuli appear to occupy the same space; and piecemeal dominance refers to small isolated parts of each eye's image dominating the binocular percept. Since luning is a change in apparent brightness (a darkening of a region), which can spread or recede over time, this particular occurrence of binocular rivalry (see Kaufman, 1963) theoretically appears also to be related to the ubiquitous contrast, and color, spreading phenomena (see Grossberg, 1987, for a catalogue and neural net theory of such phenomena), such as neon color spreading (see Nakayama, Shimojo and Ramachandran, 1990). Luning appears to emanate from the binocular overlap border and is attenuated by placing physical contours in the location of this border, that is, in the location within the homogeneous monocular field of the informational eye that binocularly corresponds to the edge of the monocular field of the noninformational eye (Melzer and Moffitt, 1991).

A potential ecological overview of the luning phenomena incorporates what recently has recently come to be known as DaVinci stereopsis (Nakayama and Shimojo, 1990). First extensively studied in modern times by Barrand (1979), **DaVinci stereopsis** refers to **binocular occlusion**, which refers to the situation in which an object in the FOV, such as one's nose, may occlude only one eye's view of more distant objects (see Gillam and Borsting, 1988). Explaining luning based on DaVinci stereopsis requires us to first analyze the optical geometric constraints imposed by the real world on an observer (see Melzer and Moffitt, 1991). That is, what real world situation, such as viewing through an aperture or viewing past an object in front of one's face, corresponds to the artificial display mode of the HMD that causes luning? The visual system may have natural responses to these situations. For example, the tendency to suppress the foreground region of an aperture may be one such response. Also, there may be no one real world situation which perfectly corresponds to an HMD display, thus leading to conflicting visual responses. There are a number of potential ecologically salient visual geometric configurations one could evoke for each type of artificial display situation; however, only recently have researchers begun to examine the visual system's natural tendencies to interpret a viewing situation in terms of these real world configurations (e.g., see Nakayama, Shimojo and Silverman, 1989; Shimojo and Nakayama, 1990).

Purpose of study

The current investigation is an applied study designed to determine how luning is influenced by display factors, the most important being the way in which the partial binocular overlap display is presented. A partial binocular overlap display can be presented in either the divergent display mode or the convergent display mode. In the **divergent display mode** the right eye's monocular region is to the right of the binocular overlap region; that is, the right eye exclusively sees the portion of the visual world to the right of the portion seen by both eyes. Similarly, the left eye's monocular region is to the left of the binocular overlap region. Conversely, in the **convergent display mode** the right eye's monocular region is to the left of the binocular overlap region, and the left eye's monocular region now is to the right of the binocular overlap region (see Figure 1). This would occur if one were binocularly viewing the visual world through an aperture. Good discussions of the visual geometry ecologically corresponding to these display modes can be found in Shimojo and Nakayama (1990) and Barrand (1979).

Melzer and Moffitt (1991) have evidence indicating that the convergent display mode induces less luning than the divergent display mode. They also claim that placing black contours within the monocular field of the informational eye in the location of the binocular overlap border also attenuates luning. We tested these image manipulations under more general conditions, including the following: by testing the placement of white as well as black contours in the locations of the binocular overlap borders; by testing variations in luminance levels; and by testing the effect of different display luminance levels, and the effect of decreasing and increasing the luminance of the monocular side regions. We measured the effect of each of these factors on the induction of luning under both the convergent and the divergent display modes.

Method

Subjects

Eighteen Army aviator student volunteers, 17 males and 1 female, took part in the experiment. Army aviator students are a population which have undergone rigorous vision screening. All had 20/20 unaided or better Snellen acuity. Furthermore, each subject's vision was checked before the experiment using the standard Armed Forces Vision Tester. Also, the accommodative/convergence relationship and the interpupillary distance (IPD) of each subject were measured and recorded. A copy of the exam data sheet is provided in Appendix A. Average age was 25, ranging from 21 to 30.

Equipment

The equipment consisted of three major components: A Hewlett-Packard HP-98731 Turbo-SRX computer graphics workstation used to generate the visual stimuli; a custom optical table configuration used to optically direct the visual stimuli from the workstation monitor to a pair of Adlerblick viewing binoculars (Edmund Scientific); and a subject booth.[1] The booth was a light proof enclosure behind the binoculars, where the subject viewed the stimuli via the binoculars and responded via an HP response keypad, or "button box."

The HP-98731 Turbo-SRX computer graphics workstation consisted of a 19-inch color SONY Trinitron monitor (1280 x 1024 pixels) for presenting visual stimuli, and a computer for generating the stimuli, recording the responses and analyzing the data. Connected to the

[1] See Manufacturers' list in Appendix B.

workstation were the experimenter's terminal allowing the experimenter to run the experimental programs and monitor the progress of each experimental session; an external monitor tied to the HP computer via a scan converter to allow the experimenter to unobtrusively view the experimental stimuli presented to the subject; and the button box, a 32-button keypad to allow the subject to respond to the visual stimulus presentations.

The optical table configuration consisted of a 4 foot x 6 foot optical table, with the workstation monitor mounted at one wide end of the table, and eight front surfaced mirrors mounted on the table to direct the visual image---the optical train---to a pair of viewing binoculars mounted on the other wide end of the table (see Figures 2, 3 and 4). The purpose of the eight mirrors was to allow the independent presentation of two channels, one to each ocular of the binoculars from the same monitor. Through the binoculars, the image on the top half of the monitor was seen by the left eye and the image on the bottom half of the monitor was seen by the right eye. The 7x50 binoculars were mounted within a fixture which allowed IPD to be adjusted precisely for each subject. Affixed to the front of the binoculars were auxiliary lenses to focus the magnified image for the optical train viewing distance. A light baffle in front of the monitor between the two optical paths was positioned to prevent cross talk between the two image channels. Filter holders in front of the binoculars allowed the placement of neutral density optical filters. The two mirrors mounted directly in front of the binoculars, L4 and R4 in Figure 4, were movable to allow adjustments corresponding to the IPD settings of the binoculars. These adjustments ensured a precisely centered image for each IPD setting.

The optical table configuration was designed to allow the horizontal extent of the monitor (1280 pixels) to match the horizontal visual extent (diameter) of each ocular of the binoculars, which was 50 degrees of visual angle. There were 25.6 pixels per degree of visual angle in the resulting images seen through the binoculars. The temporal resolution, or frame rate of the monitor, was 60 Hz, and the luminance ranged from 0.02 to 10.0 foot-lamberts (fL). The 7x50 Adlerblick binoculars had a vertex distance of 27 mm, and an exit pupil diameter of 7.14 mm.

The convex cylindrical surface of the monitor (approximately 1.5 meter radius of curvature) resulted in a focal distance disparity for the center and edges of the display seen through the binoculars. The focusing difference between the center and extreme edge of the image on the monitor, measured with a diopterscope, was approximately 0.75 diopters. To ensure a clear image for the entire FOV, the binoculars were focused with the diopterscope to -0.50 diopters (2 meters) for the center of the display. This ensured that subjects could easily accommodate to any part of the visible image.

Attached to the optical table and the subject booth was a metal frame covered by black felt cloth to prevent light leakage and to protect the optical table components. The subject booth was a light proof enclosure in which the subject was seated at an adjustable chin rest affixed in front of the binoculars. Except for the stimuli viewed through the binoculars, the subject was in darkness. Mounted in front of the subject was a call switch which rang a

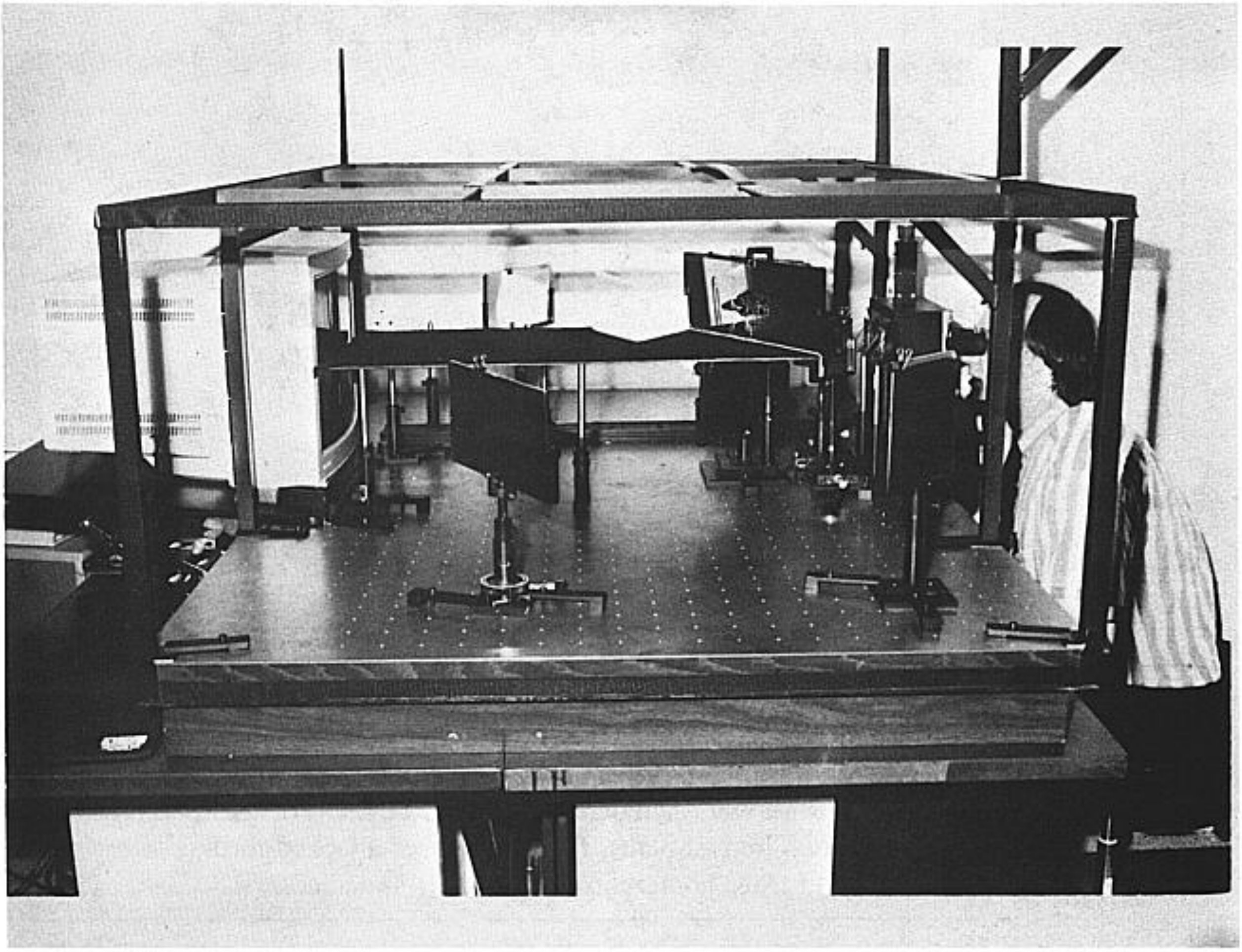

Figure 2. Photograph of the experimental setup including the optical table configuration and the subject booth. Curtains have been removed from the frames covering the table and booth in order to show the optical table configuration.

buzzer. Mounted within easy access of the subject was the button box used to register the subject's responses. Above the subject was an adjustable air vent connected to the air conditioning to allow the subject control of the temperature in the subject booth.

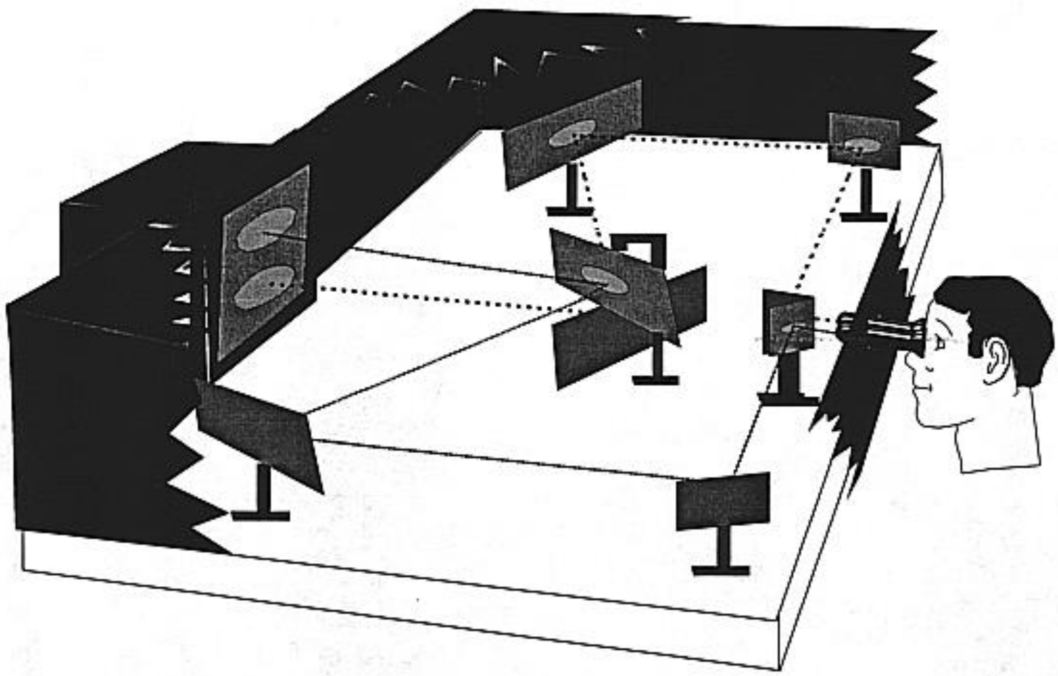

Figure 3. Perspective view of the optical table configuration, consisting of the monitor, eight mirrors, and a pair of binoculars (not to scale). The image from the top half of the monitor is directed to the left eye and the image from the bottom half is directed to the right eye. Additional equipment, not shown, include a light baffle in front of the monitor between the two optical paths, focusing lenses attached to the binoculars, and filter holders in front of the binoculars.

Stimuli

There were 22 experimental stimulus conditions which were classified into these overlapping categories. There were 1) two binocular display modes--convergent and divergent; 2) three contour types---null, black, and white---all belonging to the uniform display luminance category, which could be dim, medium or bright; and 3) two monocular luminance difference patterns--dim and bright. These are listed in Table 1 and described in detail below. Stimulus duration was 30 seconds with a 5-second dark interval between stimuli.

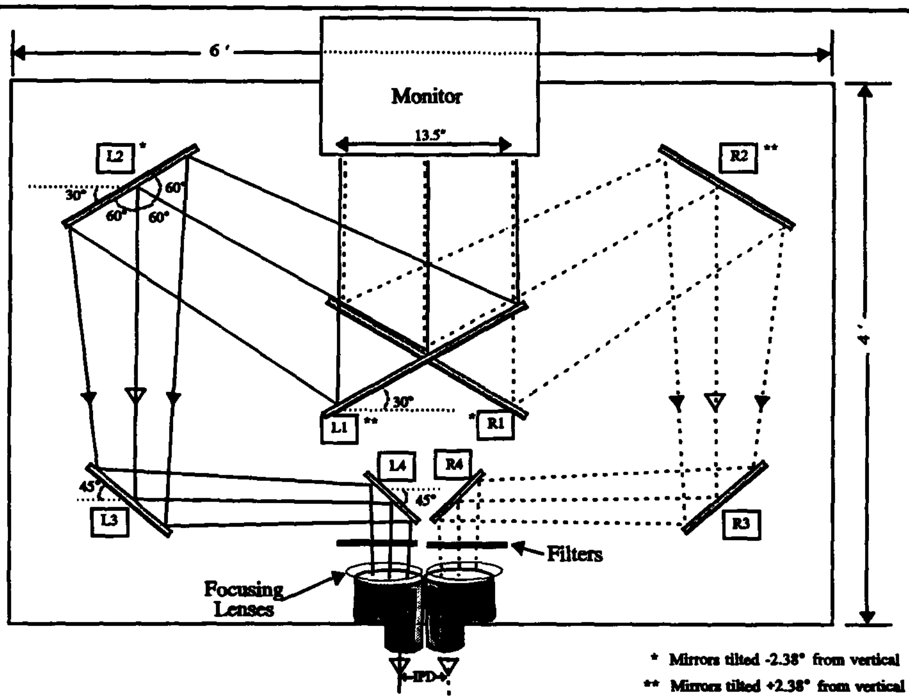

Figure 4. Top view of the optical table configuration. The image from the top half of the monitor (solid rays) is reflected down from mirror L1 to L2, and then parallel to the surface of the table, from mirrors L2 to L3 to L4 to the left ocular of the binoculars. Similarly for the right channel, the image from the bottom half of the monitor (dashed rays) is reflected up from mirror R1 to R2, and then parallel to the surface of the table from mirrors R2 to R3 to R4 to the right ocular of the binoculars. The binoculars and movable mirrors, L4 and R4, are set to correspond to each individual subjects's IPD. The resulting stimulus is shown in Figure 5.

Convergent and divergent partial binocular overlap display modes

The visual field of each eye's view through the binoculars consisted of a gray ellipse with dimensions of 30 degrees of visual angle (768 pixels horizontal diameter) x 16 degrees (410 pixels vertical diameter) against a black background. In each circular (50 degree diameter) ocular view through the binoculars, the gray ellipse was located centrally in the vertical dimension and located horizontally as described below. These ellipses represented each eye's monocular visual field, and the horizontal relationship between them defined the display mode (see Figures 5 and 6).

Table 1.
Stimulus categories.

Stimulus patterns	Description	Variations
Null contour	Monocular fields of uniform luminance. No contours located on the binocular overlap borders.	2 display modes (convergent, divergent) x 3 luminance levels of the monocular fields (dim, medium, bright). = 6 variations
Black contour	Monocular fields of uniform luminance. Black contours located on the binocular overlap borders.	2 display modes (convergent, divergent) x 3 luminance levels of the monocular fields (dim, medium, bright). = 6 variations
White contour	Monocular fields of uniform luminance. White contours located on the binocular overlap borders.	2 display modes (convergent, divergent) x 3 luminance levels of the monocular fields (dim, medium, bright). = 6 variations
Monocular luminance difference	The part of the monocular fields in the binocular overlap region were of medium luminance. The part of the monocular fields in the monocular regions were a different luminance. Luminance transition located on the binocular overlap borders.	2 display modes (convergent, divergent) x 2 luminance levels of the monocular regions (dim, bright) = 4 variations

Note: See Figure 7.

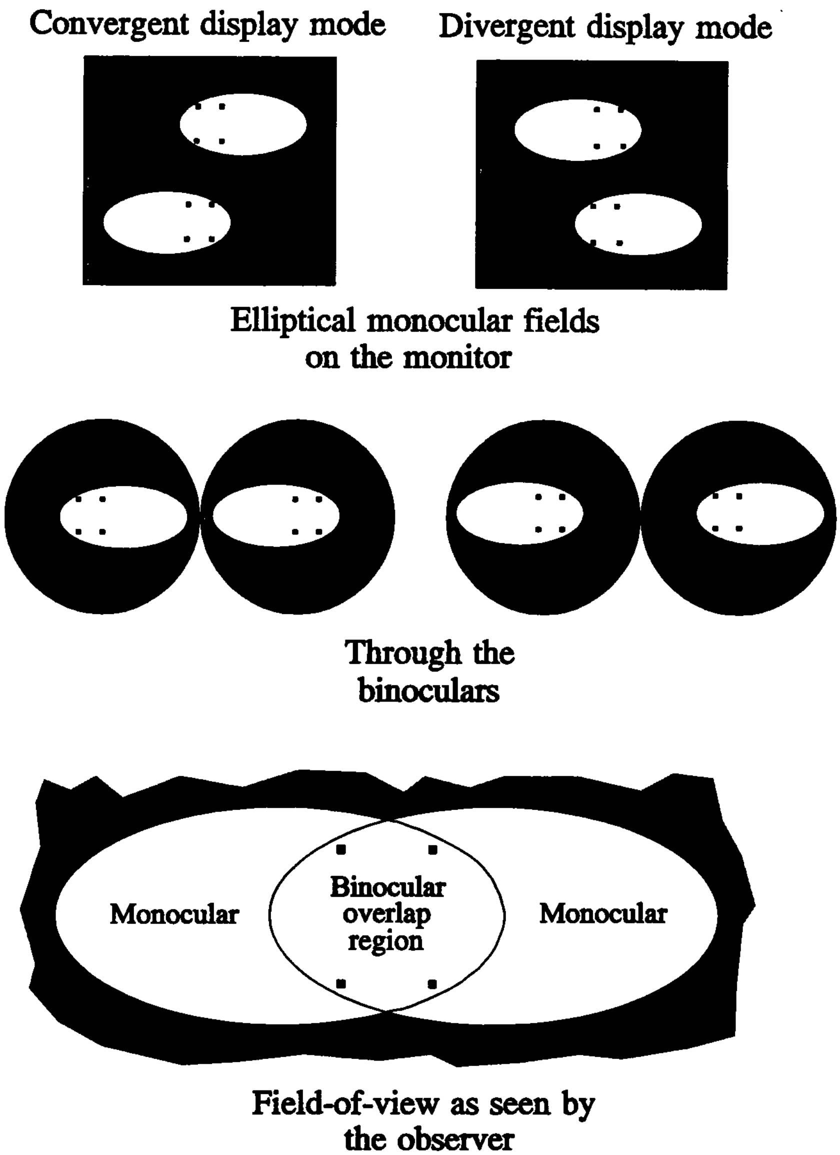

Figure 5. Convergent and divergent display modes. The top panel shows the elliptical monocular fields on the monitor for the convergent and the divergent modes. The middle panel shows the monocular fields through the binoculars and the bottom panel shows the FOV as seen by the subject when the images are properly fused. In the bottom panel, the right eye sees the right ellipse and the left eye sees the left ellipse in the divergent mode, and vice versa in the convergent mode. The purpose of the four black rectangles in each image is to serve as a stimulus for binocular locking and to prevent image slippage during binocular fusion.

If each of the ellipses was located centrally so that there was full overlap of each of the monocular fields, the total horizontal FOV was 30 degrees, the same as each monocular field. This full overlap display mode was designated the reference position.

If the elliptical field of the right eye was moved 7.5 degrees to the right of the reference position and the elliptical field of the left eye was moved 7.5 degrees to the left, the monocular fields remained the same in extent, but the total FOV was increased to 45 degrees, where both eyes saw a smaller central binocular overlap region of 15 degrees. The right eye now saw a flanking monocular region to the right of the binocular region, and the left eye a flanking monocular region to the left of the binocular region. This display mode was **divergent**, which, except for the sizes of the visual fields, is what is seen in normal human vision.

Conversely, if the elliptical field of the right eye is moved 7.5 degrees to the left of the reference position, and the field of the left eye is moved 7.5 degrees to the right, then the display mode was **convergent**, where both eyes again saw the same smaller central binocular region of 15 degrees. The total FOV again was increased to 45 degrees, but this time the right eye's flanking monocular region was to the left of the binocular region, and conversely the left eye's flanking monocular region was to the right of the binocular region. This can be simulated by looking through an aperture.

Half of the twenty-two stimuli were in the convergent display mode and half were in the divergent display mode. The gray elliptical fields were presented against a black background, which had a luminance of 0.02 fL. The luminances of the ellipses are described below.

Fusion locks

Simply shifting the images as described above is no guarantee that subjects would binocularly fuse the images. Subjects need similar stimuli common to both eyes in order to binocularly fuse images properly and to avoid image slippage, which could lead to the binocular overlap of inappropriate regions of the two monocular images. To ensure "binocular locking" of the appropriate areas, four fusion locks always were present in each eye's image in the binocular region at the appropriate location in each image. These are the (2 pixel horizontal x 8 pixel vertical) black rectangles located as shown in the ellipses in Figure 6. These were located symmetrically above and below the long axis of the ellipses, and to the right and left of the center of the fused overlap region as shown in Figure 6.

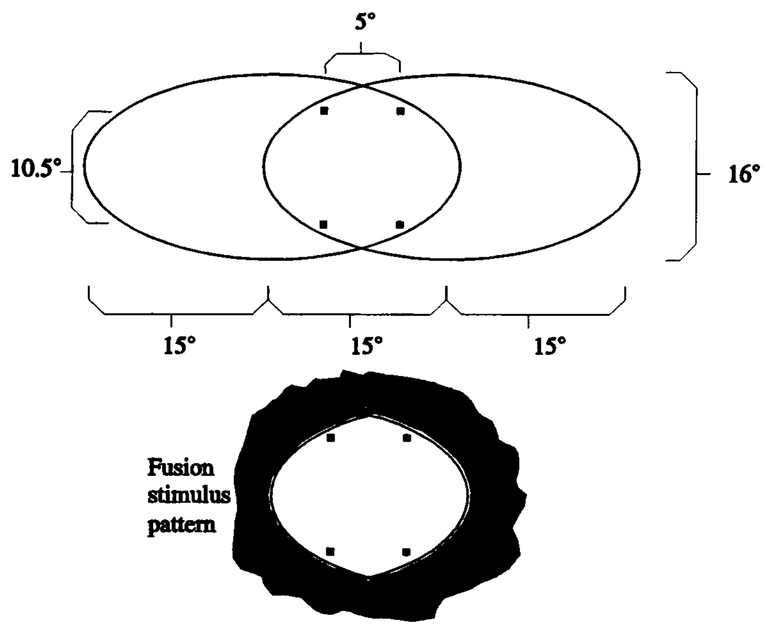

Figure 6. Stimulus dimensions. The size in degrees of visual angle are given to the right and below the overlapping monocular ellipses. The distances between fusion locks are given above and to the left. The fusion stimulus pattern, in which the same image is presented to both eyes, is shown below the ellipses. This pattern consists of the fusion locks and the binocular overlap region.

Optical convergence

Optical convergence and accommodation were both set for 2 meters. Optical convergence here refers to the angle between the optical axes of the eyes and should not be confused with the convergent display mode. Since the centers of both the right eye and the left eye images were focused at 2 meters (-0.50 diopters) through the binoculars, the right and left images also were positioned so that the eyes converged at 2 meters. This was for an average subject with an IPD separation of 64 mm. This convergence was induced by shifting each eye's image on the monitor 0.92 degrees of visual angle (22 pixels) in the nasal direction. The range of IPDs for the 18 subjects was 57 mm to 69 mm, with a mean of 64 mm. For this group of subjects, the fixed convergence thus induced convergence demands of from 1.78 meters (for a 57 mm IPD) to 2.15 meters (for a 69 mm IPD). This is less than 0.3 prism diopters (3 milliradians) of residual fusional convergence or divergence required for an image located at 2 meters.

Fusion stimulus pattern

In the course of the experiment, each subject had access, via the button box, to a fusion stimulus pattern in order to return fusion in the event it was lost. This stimulus consisted of an identical image for each eye (see bottom of Figure 6). It consisted of the four fusion locks and the binocular overlap region of the elliptical monocular fields. The luminance of this pattern was 2.0 fL against the black background. Subjects were instructed to call this pattern if they became diplopic, or if they saw more than four fusion locks, which indicated improper fusing.

Stimulus categories

There were 22 stimulus patterns, consisting of 11 stimulus categories seen under each of the two display modes. See Table 1 and Figure 7. Of these 11 stimulus categories, nine were uniform display luminance stimulus patterns in which the display luminance was constant across the elliptical monocular fields. Two were monocular luminance difference patterns in which the display luminance was not constant.

In the 18 stimulus conditions in which both elliptical monocular fields were of uniform luminance (nine uniform display luminance stimulus patterns times two display modes), the display luminances were as follows: six were dim (0.4 fL), six were medium (2.0 fL) and six were bright (5.0 fL). For each of these three luminance levels, there were three types of contour on the binocular overlap border: null, black, or white contour (Figure 7). In the six null contour patterns, no physical borders were present within the monocular fields. In the six black contour patterns, and in the six white contour patterns, respectively, black (0.06 fL) and white (10 fL) lines were located in the monocular fields at the binocular overlap borders. These black and white contours were two sided contours, i.e., lines, placed at the location of the binocular overlap borders in the fused image.

In the four stimulus conditions in which there were monocular luminance differences (dimmer and brighter side regions times two display modes), the areas of the elliptical fields composing the binocular overlap region were 2 fL and the monocular side regions were either dim (0.4 fL) or bright (5.0 fL). These were the same levels as the dim and bright levels in the uniform display luminance stimuli. In these patterns there were one sided contours---an increase or a decrease in luminance---at the location of the binocular overlap borders.

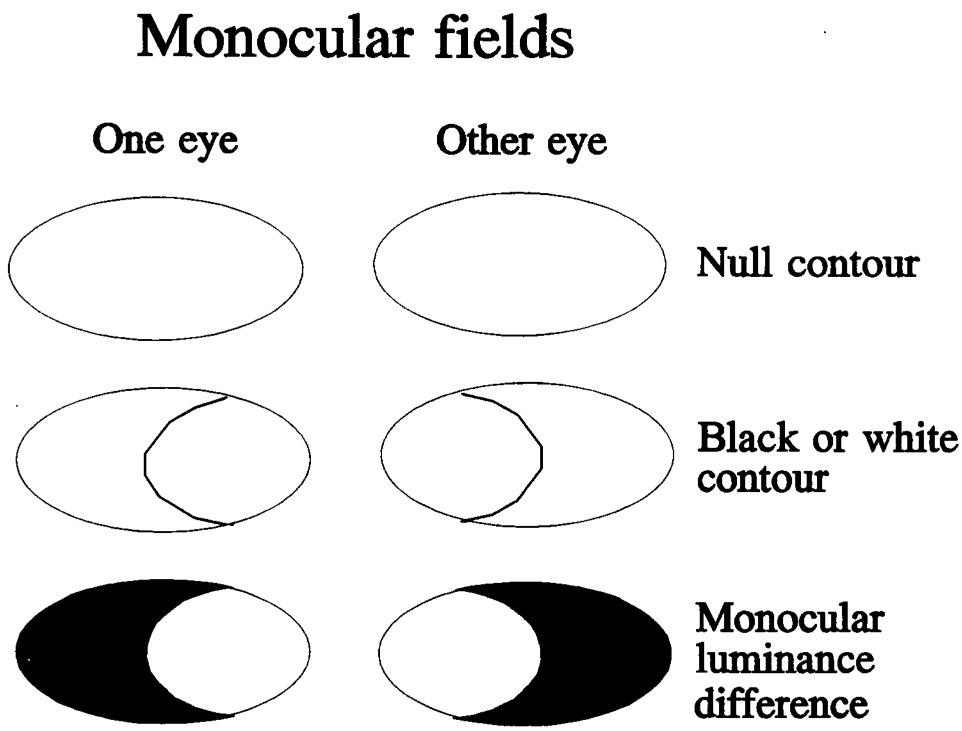

Figure 7. In the null contour stimulus conditions, the elliptical monocular fields were of uniform luminance. Contours were located on the two binocular overlap borders indicated by a black line in the black and white contour conditions. The monocular regions, indicated by shading, were brighter or dimmer than the binocular overlap region in the monocular luminance difference conditions.

Procedure

Each subject was required to read and sign a consent form and undergo a vision test (Appendix A) before the start of testing.

Prior to each experimental session, each subject was seated in the subject booth where he viewed the computer-generated stimuli through a set of binoculars. The binoculars and movable mirrors, L4 and R4, were individually positioned to correspond to the subject's IPD. The subject's head and eyes were positioned properly by displaying an alignment pattern, a square grid which covered the entire extent of the screen, to ensure that the subject could see the entire FOV through the binoculars. The subject was first given practice in obtaining binocular fusion and in the use of the button box, and was given a brief practice session with four or five stimuli, to make sure the instructions were understood. Each of the subjects had experience with the experimental setup from a previous study measuring visual thresholds.

Experimental session

For the experimental session, each subject was instructed to press one of the two response buttons continuously during the course of a trial to indicate whether luning was or was not present at any given moment. Each subject was told that the response should follow the appearance of the display throughout the course of the trial. Each subject was told that there were no good or bad responses, only that the responses should accurately reflect the appearance of the display. The subjects were instructed to use only the index finger to press one of the two keys. Experimental sessions lasted approximately 45 minutes. There was a 5-second interval between trials during which time the screen was dark. A short warning beep preceded each stimulus onset by 0.5 seconds.

The subject was instructed that, if at any time during the presentation of a stimulus, he lost fusion, or became diplopic or visually fatigued, he could press a button to bring up the fusion stimulus pattern to aid in returning fusion. The interrupted trial was restarted only after the subject pressed a release button. After the fusion stimulus pattern was released, there was a 5-second dark interval and then the warning beep before the trial was restarted.

The computer recorded the subject's responses for 25 seconds, beginning 5-seconds after stimulus onset. This 5-second delay in data recording avoided data contamination by the initial decision or reaction time. If the subject failed to respond properly either by failing to press one of the two response keys during either the initial or during the final 12.5 seconds of the data recording interval, or if the subject pressed both response keys at the same time, the following occurred: the trial was terminated; the screen went blank; and a long 5-second beep sounded. The trial was then restarted after an additional 5-second dark interval.

Data analysis

The 22 experimental conditions were presented in three blocks for a total of 66 trials. The percentage of time out of the 25-second data interval that subjects indicated they saw luning by their response was recorded for each of the 66 trials. The data for each of the 22 conditions for each subject were the overall mean responses from the three blocks. The percent luning times were analyzed by a one-way repeated measures analysis of variance (ANOVA) with 22 treatments, 6 linear trend tests, and 12 planned comparisons (Winer, 1971).

At any given moment during the trial, subjects could make one of two responses---luning present or luning absent. Although subjects were instructed to respond continuously, the amount of time change between responses ("no response"), or the time to decide on a response meant that the total response time, the amount of time subjects gave either a luning present response or a luning absent (or clear) response, was not a constant sum, (i.e., total stimulus duration minus luning present response time minus luning absent response time equals decision time). The reason this method was used rather than simply an on-off button is that, if need be, one could examine the decision time.

As a check on the data, we performed two separate analyses of the two response measures as follows: (1) amount of time luning was present measured by **percent luning time**; and (2) amount of time luning was absent measured by **percent clear time**. As the results for the percent luning and for the percent clear time were not discordant, we do not report the decision time as it provided no additional information.

We also analyzed the data using the median responses from the three blocks for each of the experimental conditions. This was performed to generate more reliable data by removing outliers (Tukey and McLaughlin, 1963; Tyler, 1991), thereby minimizing the effects of any unusual context or other influences (such as lack of familiarity initially or boredom finally). It was done here merely as a check on the stability of the data. We designate this as the trimmed data as opposed to the standard data which used each subject's mean response in the analysis.

Since our data were in the form of proportions, we also analyzed transformed data using Winer's (1971) suggested transform, where y and x equals transformed and original data respectively: $y = 2 \arcsin(x^{1/2})$. The results were the same in all respects as the results reported below for the original data.

Results and discussion

The percent luning time, and the percent clear time, for both standard and trimmed data, are given in Tables 2 and 3. The standard data are graphed in Figures 8 and 9, which show the mean percent response times, averaged over 18 subjects, where each subject's response for each condition is the mean of 3 blocks. The results for the percent clear time were consistent with the results for the percent luning time; that is, those conditions which exhibited greater percent luning time had less percent clear time and vice versa. Also the analyses of the trimmed data were consistent with the analyses of the standard data.

The overall effect of display condition on the percent time luning was present was significant for the standard data, $F(21,357) = 23.17$, $p < .001$, and for the trimmed data, $F(21,357) = 18.49$, $p < .001$. The overall effect of display condition on the percent clear time was significant for the standard data, $F(21,357) = 20.35$, $p < .001$, and for the trimmed data, $F(21,357) = 15.91$, $p < .001$.

Effect of display luminance

The effect of display luminance was examined for the null, black, and white contour conditions, where display luminance refers to the luminance level of the monocular fields. Table 4 shows the results of the linear trend ANOVAs for percent luning time and Table 5 shows the results of the linear trend ANOVAs for percent clear time. The connected dots in Figures 8 and 9 represent the conditions tested for linear trends. The linear trend of amount of luning with display luminance was not significant under either the convergent display mode or the divergent display mode, for either the null contour stimulus patterns or for the black contour patterns. Similarly, the linear trend of amount of clear time with display luminance also was not significant for any of these conditions.

However, for the white contour stimuli, there was a significant linear trend of increased luning with increased display luminance for both the convergent and the divergent display modes. Consistent with this, there was a significant linear trend of decreased clear time with increasing display luminance for the white contour stimuli for both the convergent and the divergent display modes.

The difference in display luminance results between white and black contours may be related to the fact that the display background for all the stimulus patterns was black, which matched the black contours and not the white. At first glance, one might assume that the white contour in the second eye may have had more difficulty than a black contour in obtaining stable fusion with the gray to black monocular field border seen by the first eye, thus leading to image slippage, possibly causing more luning. However, if this were true, there should be less luning with bright display luminances, because the bright gray binocular overlap border and the white contour were more closely matched in luminance. This is the opposite of the results obtained here. Phenomenally it appears that the fusion process treats the monocular field border in the noninformational eye and the contour in the corresponding location of the other noninformational eye as more or less equivalent place tokens for fusion. It would be interesting to see if this asymmetry holds for black contours and a white background. As a practical matter, we did not test patterns in which the background was white, as this would be visually detrimental to the pilot; however, see our informal observations below.

Effect of black or white contours

For both the convergent and the divergent stimulus sets, luning was reduced significantly by adding black contours or by adding white contours to the informational eye; obversely, percent clear time was increased significantly by adding the black or white contours (comparisons 4-7 in Tables 6 and 7).

Table 2.
Percent luning time.

Condition	Standard data		Trimmed data	
	Mean	SD	Mean	SD
Null contour; divergent				
Dim	87.6	10.8	89.6	6.5
Medium	86.5	22.1	87.5	22.3
Bright	85.8	22.9	88.7	22.3
Null contour; convergent				
Dim	70.1	26.1	70.8	28.7
Medium	74.8	23.3	80.7	23.9
Bright	74.6	23.0	76.1	27.9
Black contour; divergent				
Dim	35.4	30.9	30.5	35.8
Medium	37.0	31.7	37.3	43.0
Bright	34.9	33.9	36.1	39.9
Black contour; convergent				
Dim	22.0	27.3	20.2	31.1
Medium	18.7	26.9	16.0	28.8
Bright	23.8	29.6	21.4	34.0
White contour; divergent				
Dim	8.5	19.0	7.3	21.9
Medium	28.7	28.5	24.1	30.3
Bright	66.9	32.2	58.3	34.9
White contour; convergent				
Dim	21.1	27.8	20.2	29.4
Medium	25.7	26.9	25.2	35.4
Bright	54.7	32.2	58.3	34.9
Monocular luminance difference; divergent				
Dim	12.8	20.1	13.9	28.3
Bright	39.1	31.4	44.3	38.1
Monocular luminance difference; convergent				
Dim	17.5	22.0	10.9	24.4
Bright	40.4	32.0	40.8	39.3

Table 3.
Percent clear time

Condition	Standard data Mean	Standard data SD	Trimmed data Mean	Trimmed data SD
Null contour; divergent				
Dim	3.9	9.5	1.2	2.9
Medium	6.2	22.2	5.9	22.3
Bright	7.1	22.5	5.2	22.1
Null contour; convergent				
Dim	18.1	25.1	16.4	28.1
Medium	15.3	23.1	8.6	23.5
Bright	14.4	22.1	14.1	26.6
Black contour; divergent				
Dim	51.2	32.1	53.2	35.6
Medium	50.8	31.6	50.7	42.5
Bright	51.1	31.7	49.0	37.8
Black contour; convergent				
Dim	64.7	28.0	67.1	33.3
Medium	69.6	28.4	72.0	32.2
Bright	64.0	30.9	66.3	34.2
White contour; divergent				
Dim	77.1	24.7	79.0	26.2
Medium	57.4	32.3	59.3	38.1
Bright	23.3	30.7	22.5	35.1
White contour; convergent				
Dim	68.1	30.7	68.8	33.2
Medium	62.2	30.5	64.1	38.3
Bright	31.8	34.5	25.8	39.0
Monocular luminance difference; divergent				
Dim	75.1	22.0	73.4	28.4
Bright	44.6	33.0	41.1	39.6
Monocular luminance difference; convergent				
Dim	69.0	25.5	71.7	30.3
Bright	44.8	33.1	44.3	39.7

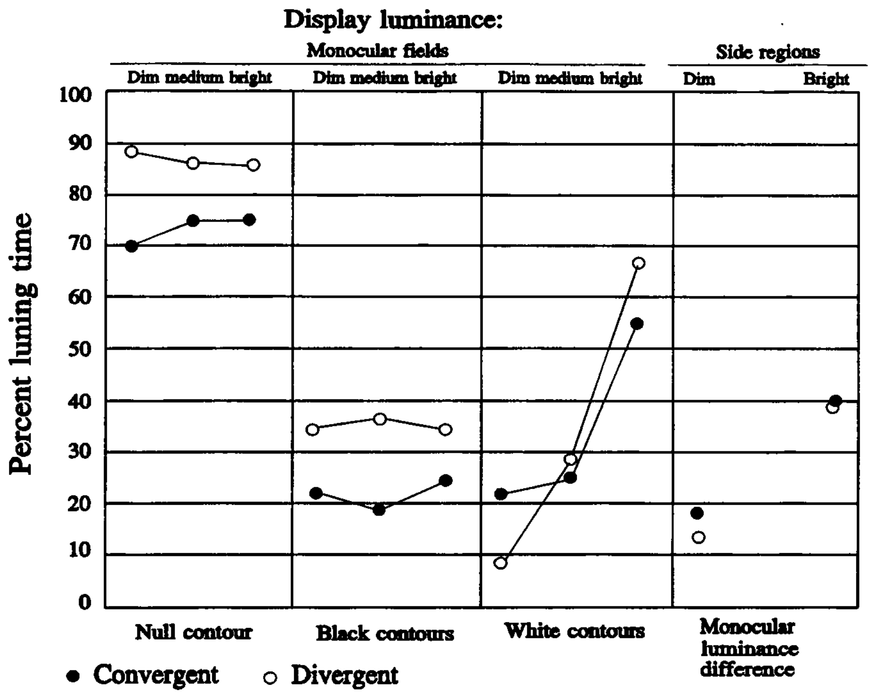

Figure 8. Percent luning time.

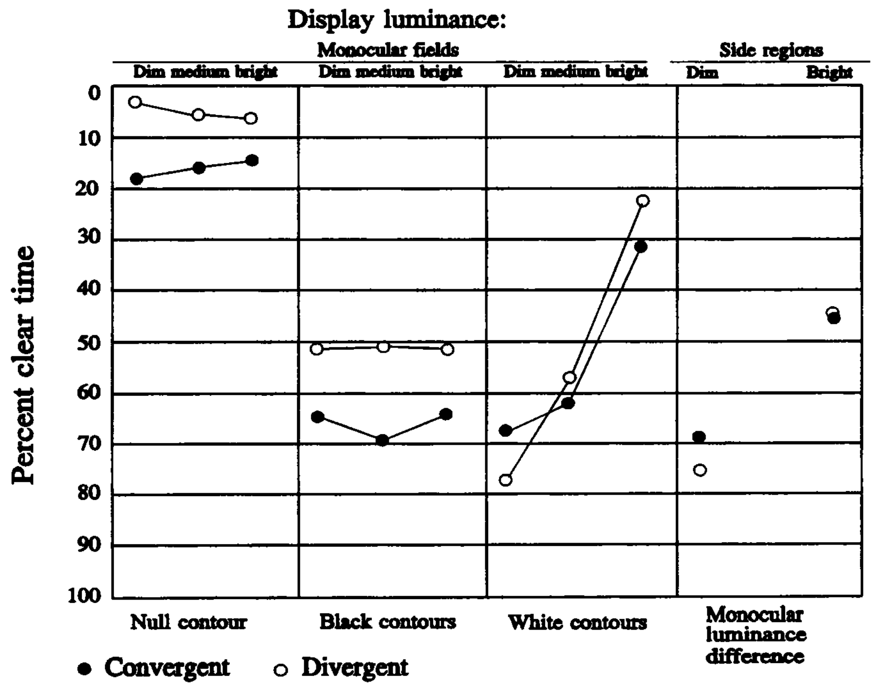

Figure 9. Percent clear time.

Table 4.
Linear trend tests for percent luning time as a function of display luminance.

Condition	Standard data F(1,357)	p	Trimmed data F(1,357)	p
Convergent, null contour	0.33	NS	0.33	NS
Divergent, null contour	0.06	NS	0.01	NS
Convergent, black contour	0.06	NS	0.02	NS
Divergent, black contour	0.00	NS	0.36	NS
Convergent, white contour	19.01	<.001	16.90	<.001
Divergent, white contour	57.37	<.001	43.19	<.001

Table 5.
Linear trend tests for percent clear time as a function of display luminance.

Condition	Standard data F(1,357)	p	Trimmed data F(1,357)	p
Convergent, null contour	0.23	NS	0.06	NS
Divergent, null contour	0.17	NS	0.19	NS
Convergent, black contour	0.01	NS	0.01	NS
Divergent, black contour	0.00	NS	0.20	NS
Convergent, white contour	21.99	<.001	21.18	<.001
Divergent, white contour	48.37	<.001	36.54	<.001

As reported above, for the white contours the degree of luning varied as a function of display luminance level---the brighter the monocular fields, the greater was the prominence of luning. This is likely due to the fact that there was lower contrast between the white contours and the bright display luminance than there was between the white contours and the dim display luminance. Thus, the white contour against a bright field may have been a weaker stimulus than against the dim field in terms of the dichoptic competition between the two eyes. Since limiting display luminance to low levels is operationally unrealistic, white contours are not recommended to reduce luning in HMDs. In addition, there would likely be a deleterious effect on threshold in the vicinity of high contrast white contours. An alternative explanation is that with the dim display luminance, the luning was there but less noticeable near the high contrast white contours; even so, small proximate targets might require greater contrast to be seen.

Table 6.
Planned comparisons for differences in percent luning time

Comparison	Standard data F(1,357)	p	Trimmed data F(1,357)	p
1. Null contour: convergent v divergent	9.14	<.005	5.66	<.05
2. Black contour: convergent v divergent	10.31	<.005	8.33	<.005
3. White contour: convergent v divergent	0.04	NS	0.06	NS
4. Convergent: null contour v black contour	134.76	<.001	112.22	<.001
5. Divergent: null contour v black contour	130.44	<.001	101.75	<.001
6. Convergent: null contour v white contour	78.13	<.001	59.58	<.001
7. Divergent: null contour v white contour	136.06	<.001	107.16	<.001
Monocular luminance difference:				
8. Bright: convergent v divergent	0.03	NS	0.04	NS
9. Dim: convergent v divergent	0.05	NS	0.03	NS
10. Convergent: bright v same	19.92	<.001	18.49	<.001
11. Divergent: bright v same	37.78	<.001	21.71	<.001
12. Convergent: dim v same	55.21	<.001	56.63	<.001
13. Divergent: dim v same	91.31	<.001	63.02	<.001
14. Bright v dim	20.33	<.001	21.16	<.001

Note: Same = Null contour at medium display luminance

It is interesting that the black contour conditions did not show the same effect of display luminance as the white contour conditions. It is possible that the effect of the black contours peaked outside of our display luminance testing range or maybe the pertinent fact is that the black contours matched the dark background. This latter case might entail a Gestalt type of explanation---the visual system interprets the black contour as being a border between the visual field and the background which is also black. Thus, there is less ambiguity and less rivalry and the background is suppressed more thoroughly, or perceptually "scissioned" into a different depth plane (see Matelli, 1974). A large number of factors are known to affect binocular rivalry (e.g., Hollins, 1980; O'Shea and Blake, 1986). A future study might independently vary the contrasts (or colors) of the contours, the monocular fields, and the background.

Table 7.
Planned comparisons for differences in percent clear time

Comparison	Standard data F(1,357)	p	Trimmed data F(1,357)	p
1. Null contour: convergent v divergent	5.19	<.05	2.73	NS
2. Black contour: convergent v divergent	11.41	<.001	10.52	<.005
3. White contour: convergent v divergent	0.10	NS	0.02	NS
4. Convergent: null contour v black contour	126.67	<.001	105.73	<.001
5. Divergent: null contour v black contour	103.15	<.001	75.57	<.001
6. Convergent: null contour v white contour	73.05	<.001	54.70	<.01
7. Divergent: null contour v white contour	110.29	<.001	84.20	<.001
Monocular luminance difference:				
8. Bright: convergent v divergent	0.00	NS	0.03	NS
9. Dim: convergent v divergent	0.06	NS	0.02	NS
10. Convergent: bright v same	14.61	<.001	14.65	<.001
11. Divergent: bright v same	24.61	<.001	14.20	<.001
12. Convergent: dim v same	48.32	<.001	45.70	<.001
13. Divergent: dim v same	79.51	<.001	52.20	<.001
14. Bright v dim	25.09	<.001	20.41	<.001

Note: Same = Null contour at medium display luminance

Effect of monocular luminance difference

In the monocular luminance difference patterns, the luminances of the parts of the monocular fields in the monocular regions (for the informational eyes) were either dim or bright, while the luminance of the parts in the binocular overlap region were medium. The condition with the dim monocular side regions had significantly less luning than the condition with the bright monocular side regions, and each of these had significantly less luning than the null contour condition, where the side regions were of the same---medium---luminance as the central region. These differences were consistent with the percent clear time data (comparisons 10-14 in Tables 6 and 7).

The monocular luminance difference patterns are similar to the black and white contour patterns in that there is a physical border located within the monocular field delimiting the monocular and binocular regions. Placing any type of physical border within the monocular field at the location of the binocular overlap border, whether white or black contours or the luminance transition in the monocular luminance difference patterns, appears to reduce luning.

The dim and bright monocular luminance difference patterns are similar to the dim and bright patterns with contours in that they have the same luminance levels in the monocular regions. Both the black and white contours substantially reduce luning when the monocular region is of dim or medium luminance, as do the monocular luminance difference patterns. The white contour patterns and the monocular luminance difference patterns begin to fail when the monocular region is bright. The difference in the pattern of results between the black contour, the white contour, and the monocular luminance difference conditions may be due to a number of factors, including the possibility that when there is a black background the black contours may be superior in locking fusion, and they may be better at competing dichoptically, thus more effectively reducing the interocular suppression from the other eye.

Effect of convergent and divergent display modes

The results of the planned comparisons are given in Table 6 for the percent luning times and in Table 7 for the percent clear times.

The convergent display mode had significantly less luning and more clear time than the divergent mode for the null contour and for the black contour stimulus conditions (comparisons 1 and 2 in Tables 6 and 7). This was true for three out of the four ways we examined the data; only for one---the percent clear time trimmed data---for the null contour, did the difference marginally fail to reach significance.

There was no systematic effect of display mode for the white contour patterns, or for the monocular luminance difference patterns (comparisons 3, 8 and 9 in Tables 6 and 7).

For the null contour and the black contour conditions, the results showing a reduction in luning for the convergent display mode compared to the divergent display mode, and a reduction for the black contours compared to the null contours confirm Melzer and Moffitt's (1991) findings. The average reduction in luning from the divergent mode to the convergent mode was about the same for the null contour conditions (13.5 seconds) and for the black contour conditions (14.3 seconds), a finding which supports the independence of the effect of display mode and the effect of black contours on luning. **Thus, with respect to the attenuation of luning, the convergent display mode with black contours appears to be the best display condition.** How other visual factors, such as target thresholds, are influenced by these contours, or the binocular overlap border per se, is another question (see Klymenko, Verona, Beasley and Martin, 1993; also see Fox and Check, 1968).

Fusion stimulus pattern calls

The computer recorded the number of times that each subject called the fusion stimulus pattern for each of the two display modes. There was no large systematic bias for either display mode. Only one-third of the 18 subjects called the fusion stimulus pattern.

The number of calls during type of display mode for each of these six subjects were as follows (convergent calls, divergent calls): (0,1), (0,1), (4,7), (1,7), (1,0), (1,0). Only two subjects showed a noticeable bias, which was for divergent calls.

Caveat on the method and additional data analysis

Our method of recording the percentage of time a percept was present, in our case the presence or absence of luning, is used widely to measure the strength of alternative perceptual responses with fluctuating stimuli, such as binocularly rivalrous patterns (e.g., Melzer and Moffitt, 1991) and ambiguous figure-ground patterns (e.g., Klymenko and Weisstein, 1986). One should keep in mind the additional influences of experimental context and the subject's criterion bias. Experimental context here refers to the complete set of patterns, in our case, the 22 stimulus patterns. During a trial, the subject is required at every moment to make a categorical response---yes, luning present, or no, luning not present--- to a stimulus effect which can vary continuously in magnitude. Where the subject decides to set his criterion, for presence or absence, is largely determined by the set of stimuli he has seen---the experimental context---as well as personal idiosyncratic factors. For instance, if only weakly luning patterns or only strongly luning patterns were present, the subject would be likely to make finer discriminations between stimuli and would set his criterion accordingly. Conversely, if extreme anchor points were present in the set of stimuli, then subjects would be less likely to systematically make finer discriminations between similar stimuli (see Parducci, 1968; Marks, 1993). Also, subjects will shift their criterion during the course of viewing a stimulus. While not possible in the current context, one could have the subject make direct comparisons between pairs of stimuli, where the stimuli are presented simultaneously (see Klymenko, Verona, Beasley, Martin and McLean, 1994). We point this out only to alert the reader that the current results based on different subjects with different and shifting criterion points and legitimate for indicating the relative differences in luning magnitude between stimuli, should not be interpreted as indicating the absolute percentage of time luning was always present or always absent (see Fox and Check, 1972). Subject variability, indicated by the standard deviations in the data tables may likely be due to differences in criterion settings between subjects as opposed to differences in perception per se.

Above, we reported the subject's responses for the 25-second data interval. The computer also independently recorded the data for smaller temporal intervals, the initial 12.5 seconds and the final 12.5 seconds of the data interval. These means (for standard data) are shown in Table 8 for percent time luning present. There was a general trend with subjects indicating more luning in the final compared to the first interval. The overall effect of display condition on the percent time luning was present was significant for the initial interval, $F(21,357) = 22.21$, $p < .001$, and for the final interval, $F(21,357) = 21.18$, $p < .001$. The results of the statistical analyses are shown in Tables 9 and 10. The results of the two smaller temporal intervals are consistent with the data reported for the larger 25-second interval; compare Table 9 with Table 4 and Table 10 with Table 6. These data are of interest in that they also give us a rough indication of the time course of the relative magnitude of luning; however, it should be noted that in the current design, time course effects are confounded with the criterion shifts noted above. The results for both the smaller temporal intervals were consistent with the results for the larger temporal interval. **This indicates that luning occurs quickly; it is not a transitory phenomenon; and it does not attenuate quickly.**

Informal observations

In addition to the luning effect per se, the monocular regions can look different than the binocular overlap region. This likely is due to binocular brightness combination---either binocular additivity and/or binocular brightness averaging (see Blake and Fox, 1973; Fry and Bartley, 1933; Levelt, 1965). In the displays tested here, the monocular regions overall tend to look darker than the binocular overlap region. Phenomenally, this may be seen as a very subtle difference in apparent brightness, particularly for lower display luminances. This is as one might expect if the perceived brightness of the monocular regions were the binocular combination of the monocular field from the informational eye with the dark background from the noninformational eye, and the perceived brightness of the binocular region was the binocular combination of the two monocular fields. As expected, this difference between monocular and binocular regions is less noticeable for dimmer display luminances (DaSilva and Bartley, 1930; Engel, 1967). This combination factor may interact with the prominence of luning by making it less noticeable for dim display luminances and may have contributed to the lower reported magnitude of luning for both the dim luminances with the high contrast white contour stimuli and for the dim monocular luminance difference patterns.

We also have examined informally several displays similar to the ones reported here, where we varied the luminance and color of the background and the monocular fields. If the background is white rather than black and the monocular fields held at the same intermediate gray luminances, then bright rather than dark crescents will appear in the monocular regions. This brightening effect, like the darkening effect, generally appears to emerge at the binocular overlap border and to spread outward into the monocular regions. Changes are slow and discontinuous in that large areas of the monocular region may appear to brighten at once. Phenomenally, the luning effect appears more pronounced with a white background than with a black background; however, we currently do not know what increase in luminance is equivalent to what decrease in luminance of the background with respect to the monocular fields. With the white background, the luning in the monocular regions very noticeably resembles binocular lustre, which refers to the shiny metallic appearance obtained when fusing a white and a black region.

If the ellipses and background are colored, for example red ellipses against a green background, then the luning crescents will be the color of the background, green in this case. Phenomenally, they are the same as described above and appear as pronounced as in the white background case. As with binocular rivalry in general, there is no additive color mixing per se, whatever the color combination (i.e., green ellipses against a red background are not

Table 8.
Percent luning time for short temporal intervals.

Condition	Initial 12.5 second interval Mean	SD	Final 12.5 second interval Mean	SD
Null contour; divergent				
Dim	79.9	14.1	95.6	9.3
Medium	79.4	21.1	93.6	23.6
Bright	81.3	21.5	90.2	24.7
Null contour; convergent				
Dim	59.8	27.6	81.2	27.5
Medium	67.8	23.3	81.8	26.1
Bright	66.1	23.9	83.1	26.1
Black contour; divergent				
Dim	35.9	30.8	34.9	32.0
Medium	33.6	30.3	40.4	33.7
Bright	32.5	32.4	37.3	37.1
Black contour; convergent				
Dim	17.1	23.1	26.9	33.7
Medium	16.1	21.5	21.2	33.1
Bright	22.2	25.7	25.4	34.9
White contour; divergent				
Dim	8.1	19.5	8.9	19.2
Medium	23.8	25.1	33.7	34.7
Bright	60.8	31.3	73.0	35.1
White contour; convergent				
Dim	19.8	24.8	22.3	33.3
Medium	20.3	22.6	31.0	33.5
Bright	44.3	28.9	65.6	37.3
Monocular luminance difference; divergent				
Dim	14.6	19.6	11.0	21.5
Bright	32.5	28.1	46.4	37.5
Monocular luminance difference; convergent				
Dim	17.4	22.0	17.6	23.6
Bright	33.7	28.0	47.0	37.2

Table 9.
Linear trend tests for percent luning time as a function of display luminance for short temporal intervals.

Condition	Initial 12.5 second interval		Final 12.5 second interval	
	F(1,357)	p	F(1,357)	p
Convergent, null contour	0.77	NS	0.04	NS
Divergent, null contour	0.04	NS	0.37	NS
Convergent, black contour	0.52	NS	0.03	NS
Divergent, black contour	0.22	NS	0.07	NS
Convergent, white contour	11.63	<.001	23.76	<.001
Divergent, white contour	54.01	<.001	52.12	<.001

Table 10.
Planned comparisons for differences in percent luning time for short temporal intervals.

Comparison	Initial 12.5 second interval		Final 12.5 second interval	
	F(1,357)	p	F(1,357)	p
1. Null contour: convergent v divergent	14.28	<.001	4.72	<.05
2. Black contour: convergent v divergent	14.05	<.001	6.48	<.05
3. White contour: convergent v divergent	0.44	NS	0.05	NS
4. Convergent: null contour v black contour	123.91	<.001	125.94	<.001
5. Divergent: null contour v black contour	124.60	<.001	117.71	<.001
6. Convergent: null contour v white contour	77.45	<.001	68.28	<.001
7. Divergent: null contour v white contour	141.93	<.001	113.64	<.001
Monocular luminance difference;				
8. Bright: convergent v divergent	0.03	NS	0.01	NS
9. Dim: convergent v divergent	0.15	NS	0.54	NS
10. Convergent: bright v same	22.58	<.001	15.31	<.001
11. Divergent: bright v same	42.67	<.001	28.36	<.001
12. Convergent: dim v same	49.36	<.001	52.29	<.001
13. Divergent: dim v same	81.56	<.001	86.52	<.001
14. Bright v dim	11.39	<.001	26.61	<.001

Note: Same = Null contour at medium luminance.

perceived as yellow in the monocular regions). The actual color combinations, opponent or nonopponent, do not appear to be a salient factor. The color of the monocular region does appear to be modified by the background, as one might expect from dichoptic color mixing, with the luning then appearing in the already chromatically modified monocular region as a very pronounced color shift to the background color.

These observations support the notion that luning is a binocular rivalry phenomenon, occurring primarily as a result of the edge of the monocular field of the noninformational eye being dichoptically superimposed on the homogeneous monocular field of the informational eye. In dichoptic stimulation, the homogeneous area adjacent to a suppressor edge in one eye is known to dominate homogeneous regions in the contralateral eye, and to spread its influence across the binocular percept (Kaufman, 1963, 1964). In our displays, the suppression within the monocular region---luning---is based on distance to the binocular overlap border, i.e., distance to the sharp border between the monocular field and the background in the noninformational eye. This dichoptic competition and the point by point luminance and color differences between the eyes appear to account for the phenomenal appearance of these displays.

Placing any high contrast edge in the informational eye at the location of the binocular overlap border appears to attenuate luning by halting the spread of suppression from the non-informational eye. In other words, the physical contour in the monocular field of the informational eye attenuates the interocular suppression from the border of the monocular field in the noninformational eye. It does this because the contour is a strong stimulus, in terms of rivalry competition between the two eyes, and it also matches the stimulus characteristics of the noninformational eye's border leading to better fusion (i.e., singleness of vision). At higher levels in the visual system, the monocular field border and the contour are equivalent place tokens of similar shape; at lower levels, they may differ in that one is a one-sided contour and the other is a two-sided contour. It is still controversial as to where, throughout the multiple levels of the visual system, rivalry occurs (e.g., see Yu and Blake, 1992), and even if it still occurs, albeit unnoticed, during the fusion of identical images. Here, we have limited the term rivalry to dichoptic stimuli. Alternatively, softening the suppressor edge in the noninformational eye with a luminance rolloff has been shown to reduce luning (Moffitt, 1989). This apparently weakens the monocular field edge's competitive strength as a dichoptic stimulus.

In our observations, the contrast between the contour and the surrounding monocular field appears to be important, whereas the color relationship between the contour and the other areas of the display appears less relevant. For example, it is irrelevant if the monocular fields are red or blue, etc., and the background is green or yellow, etc.; the contour will attenuate luning whether black or purple, etc. This last statement may appear to contradict our results for the white contours; however, we believe that those results can be interpreted in terms of achromatic luminance contrast. Confirming this, however, requires precise psychophysical measurements to separate achromatic contrast and color relationship effects. How this ties in precisely with the asymmetry in our obtained results for white and for black contours currently is unknown as there are other complicating factors such as the influence of the surrounding area of the background versus the area of the dichoptically presented monocular field.

Conclusions

Of the conditions that we investigated, the convergent display mode with black contours appears to be the best method for consistently reducing luning. How ultimately the advantages trade off with the disadvantages in HMDs will depend on a number of factors including the visual tasks required.

There is a vast and growing literature going back a century on binocular rivalry and suppression, and on the physical stimulus properties which promote monocular dominance (e.g., see Uttal, 1981). For instance, we know sharp edges dichoptically dominate blurred edges and moving stimuli dichoptically dominate static stimuli (see Fox, 1991, for a review). We have yet to find evidence that luning is anything more than a form of binocular rivalry and suppression. Therefore, it is likely that the conditions which are strong dichoptic competitors to the monocular field border of the noninformational, or luning-inducing, eye will, therefore, reduce the luning in the monocular region of the informational eye. The homogeneous monocular field exhibiting luning, that is suppression from the non-informational eye, is a weak dichoptic competitor in binocular rivalry. Contours dichoptically dominate homogeneous regions (Kaufman, 1963). The black contour is a stronger dichoptic competitor than a homogeneous region; this edge pulls in its local surrounding area into the binocular percept (Kaufman, 1963). We have found that a homogeneous area (null contour) is a weak dichoptic competitor, where luning is seen more than 50 percent of the time, while the black contour is a strong dichoptic competitor, where luning is seen less than 50 percent of the time. Here the black contour is a stronger competitor than the monocular field border of the luning inducing noninformational eye. The contrast between the black contour and its local area appears to be the important factor. The white contour also is a strong dichoptic competitor when its contrast with its local area is high, that is the surrounding region is of dim or medium brightness. When the contrast between the white contour and its local surround is reduced as it is under bright display luminance, then luning dominates the binocular percept. This appears also to be true of the monocular luminance difference patterns. The local border contrast is greater for the dim than for the bright monocular luminance difference patterns, and this produces a greater reduction in luning. Local contrast appears to be the most important factor. Other minor factors may be differences in the areas of the regions, differences in luminance between areas (i.e., the luminances of the monocular field and the dichoptic background), absolute display luminance level, and possibly the polarity of contrast. It is still open to debate as to what analysis of stimulus characteristics (e.g., spatial frequency channels, luminance gradients, etc., see Frisby, 1980) best accounts for the binocular rivalry data, and if an ecological analysis (Barrand, 1979), which we discuss elsewhere (Klymenko, Verona, Beasley, Martin and McLean, 1994), is the most parsimonious theoretical overview. Elucidating the differential effect of the convergent and divergent display modes on luning is an interesting area for further research.

In summary, luning is the result of the dichoptic competition from the monocular field border of the noninformational eye. Placing an edge, high in contrast with its local field, will increase the dichoptic strength of the informational eye. Additional binocular processes, such as binocular summation, contribute to the appearance of the FOV in these displays.

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Appendix A.

Eye exam data sheet

Psychophysical Assessment of Visual Parameters in Electro-optical Display Systems

VISUAL EXAM

Subject #__________________ Age:_____ Date:___________

Old RX: R.E.____________________ L.E.______________________
for distant vision (Yes) (No)
for near vision (Yes) (No)
Bifocal (Yes) (No)

AFVT - with glasses if required for distance #3, #2, #1

VA R.E. line_____20/____ Lateral Phoria #____ _____
FAR L.E. line_____20/_____ Vertical Phoria #____ _____
LP = XO >11; VP = Rt Hyper >5, .5 steps

Stereopsis thru line# _______
Lateral Phoria @ Near #_______ ______ LP = XO >13

AUTO REFRACTION (ARK 2000) P.D. _________

O.D. ___________________________
O.S. ___________________________

SUBJECTIVE REFRACTION: (Green>Red) X-CYL at far
O.D. _________________________ 20/ O.D._______ SPH
O.S. _________________________ 20/

Lateral Phoria @ Far _________ Vertical Phoria_______

Lateral Phoria @ Far with -1.00 D _________

Lateral Phoria @ 50 cm _________ X-CYL @ 50 cm O.D._______SPH
Lateral Phoria @ 50 cm +1.00 D __________
Lateral Phoria @ 50 cm -1.00 D ___________
Calculated ACA ratios far minus _______
near plus _______
near minus_______

Appendix B.

Manufacturers' list

Hewlett-Packard Company
3404 East Harmony Road
Fort Collins, Co 80525

Edmund Scientific Co.
Edscorp Building
Barrington, NJ 08807